Development and Bench-Scale Testing of a Novel Biphasic Solvent-Enabled Absorption Process for Post-Combustion Carbon Capture

(DE-FE0031600)

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DOE/NETL Carbon Management and Natural Gas & Oil Research Project Review Meeting (Virtual)

August 16, 2021

Presentation Outline

- Project Overview
- Technical Background
- Technical Approach and Project Scope
- Progress and Current Status of Project
- Plan for Future Testing / Development / Commercialization

Project Objectives and Participants

Objectives:

- Design, fabricate, and test an integrated 40 kWe bench-scale capture unit with synthetic and actual coal flue gas
- Develop and evaluate solvent handling options
- Demonstrate the technology progressing toward achieving DOE's Transformational Capture Goals (95% CO_2 purity & $30/tonne of CO_2 captured)

Participants:

- University of Illinois:
  - IL State Geological Survey: Solvent & process development
  - IL Sustainable Tech Center: Analysis; EH&S; commercialization plan
  - Facilities & Services: Bench-scale unit installation
  - Abbott Power plant: Host site
- Trimeric Corporation: Process design/equipment specs; TEA support
- ITG Henneman Engineering: Detailed engineering design; startup support

Project Schedule and Budget

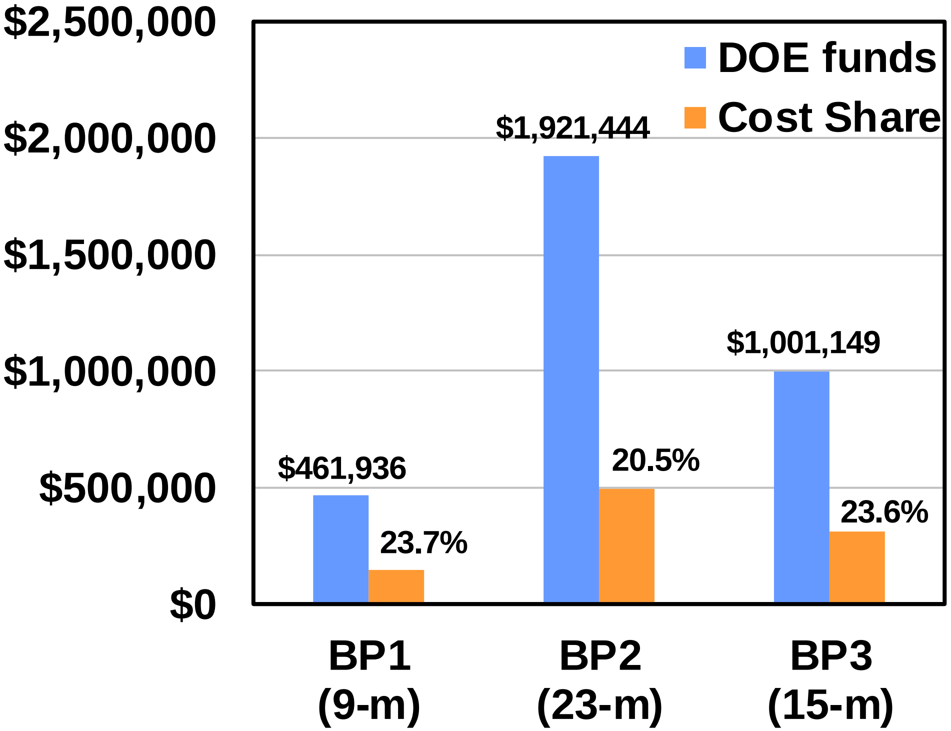
Project Duration:

47 mon (4/6/18–2/28/22)

- BP1: 9 mon (4/6/18-1/5/19)
- BP2: 23 mon (1/6/19-11/30/20)
- BP3: 15 mon (12/1/20-2/28/22)

Funding Profile:

- DOE funding of $3,384,529
- Cost share (in-kind and cash) of $949,741 (~22%)



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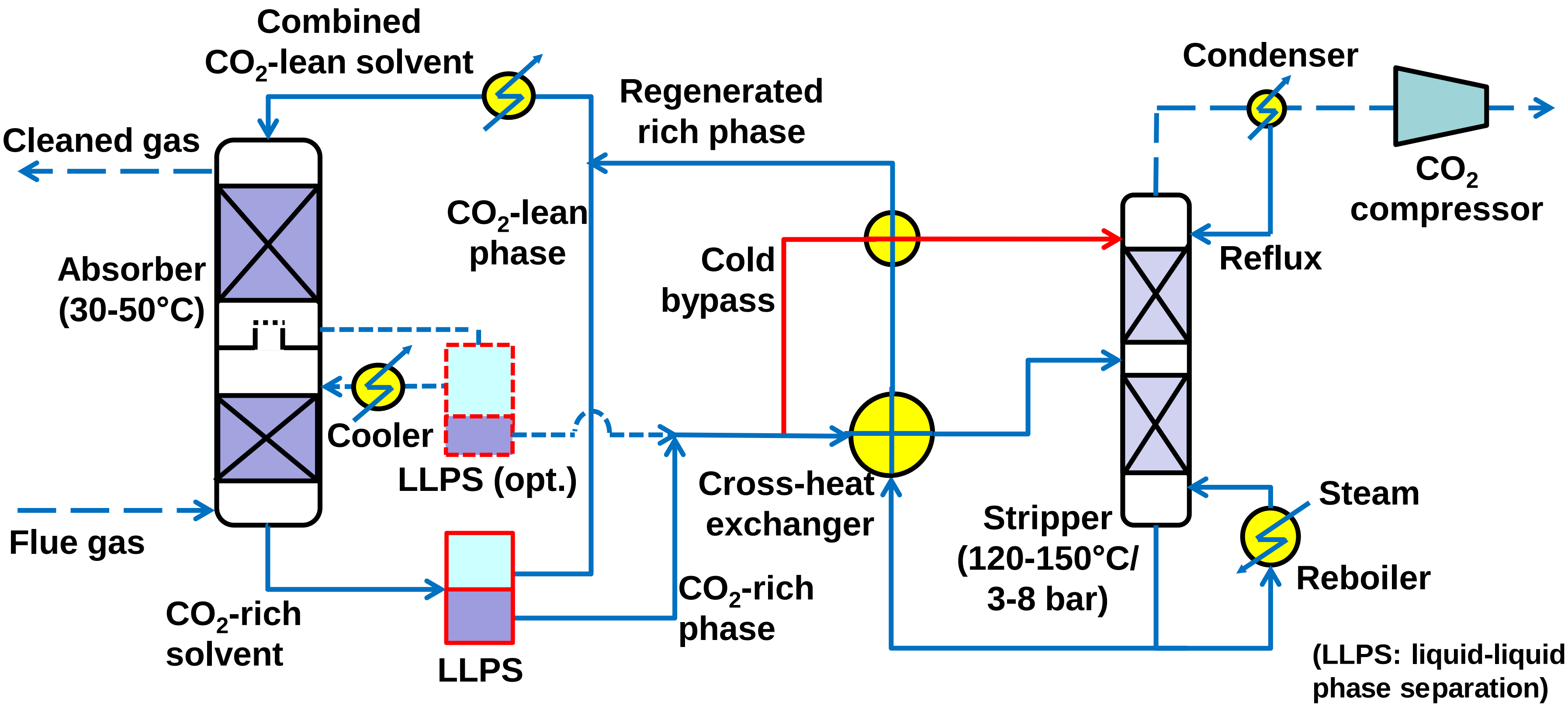
Biphasic CO_2 Absorption Process (BiCAP)



Impact on absorber:

- High absorption rate compared with MEA
- Applicable for high-viscosity solvents via multi-stage LLPS to enhance rate

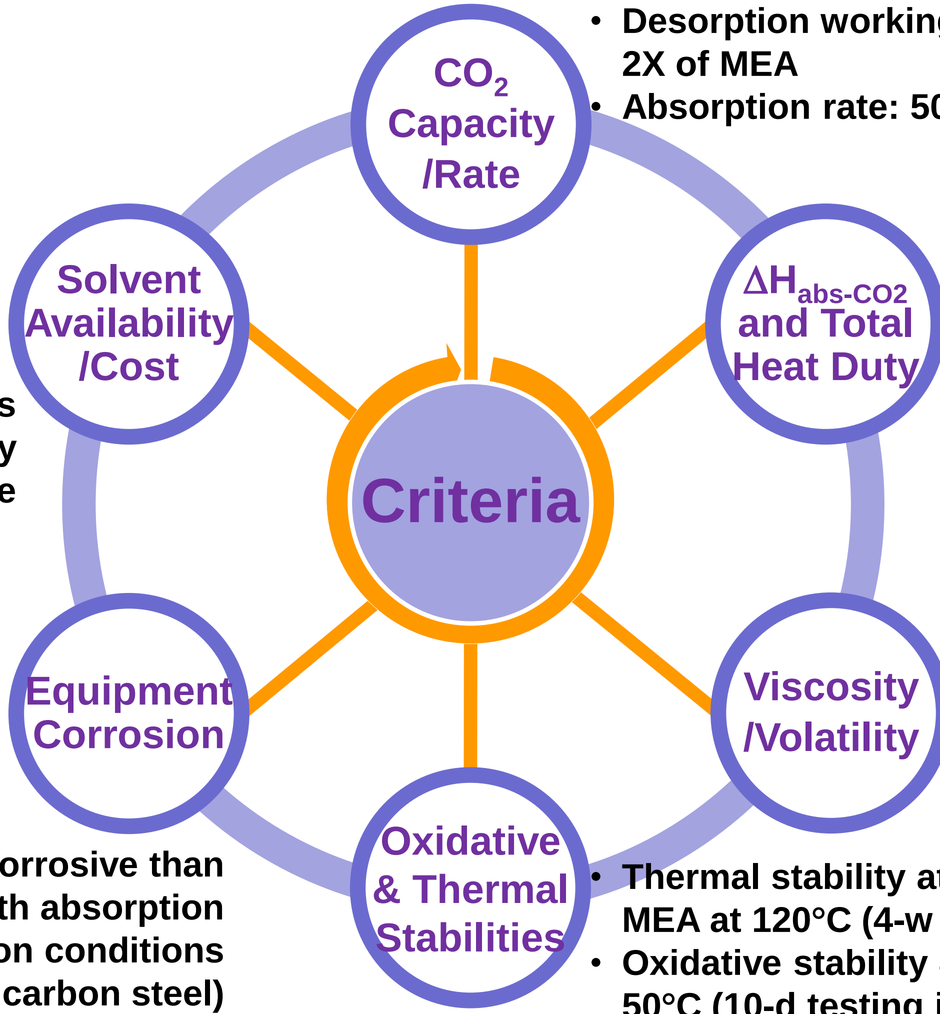
Impact on stripper:

- Reduced solvent mass to stripper leads to low sensible heat use and small equipment size
- Enriched CO_2 loading leads to high stripping pressure (i.e., low stripping heat and CO_2 compression work)
- Cold bypass further reduces stripping heat

Novel BiCAP Solvents and Previous Work

Biphasic solvents:

- Water-lean (<30% water);
- Tunable partitions of volume and species in two phases



- **Desorption working capacity: 2X of MEA**
- **Absorption rate: 50% > MEA**

Reboiler heat duty: 30-50% < MEA in 10 kWe lab tests

CO_2-saturated heavy phase viscosity: ≤45 cP @ 40°C

- **Thermal stability at 150°C ≈ MEA at 120°C (4-w testing)**
- **Oxidative stability 8X > MEA at 50°C (10-d testing in 96% O_2)**

2-3X less corrosive than MEA under both absorption & desorption conditions (<20 μm/yr for carbon steel)

All components commercially available

Prior Work of Technology Development

Jan 2013

- Lab proof-of-concept studies of biphasic solvents
- Funding: UI (Part of dissertation research)

Jul 2015

- 10 kWe lab scale: Separate absorber & stripper testing
- Solvent screening & characterization (~80)
- Funding: DOE / UI

Apr 2018

- 40 kWe bench scale: Closed-loop system at a power plant
- Solvent handing studies (emissions, reclamation, etc.)
- Funding: DOE / UI

→ Skid Testing

Feb 2022

Prior Work

Current Project

Comparisons (2011$): BiCAP vs. Case 12

	Units	USDOE Case 12 (Econamine)	BiCAP
Energy requirements			
Gross Generating Capacity	MWe	801.9	704.2
CCS De-rate			
Compression & Dehydration	MWe	44.9	27.3
Pumps, Blower, etc.	MWe	30.3	15.5
Regeneration Steam De-rate	MWe	139.1	78.3
Total De-rate	MWe	214.3	121.1
Base Plant Auxiliary Load	MWe	37.6	33.1
Net Electricity Produced	MWe	550.0	550.0
CCS Costs (2011$)			
Purchased Equipment Cost	MM$	127.52*	79.25
COE - No TS&M	mills/kWh	137.3	116.5
Cost of CO_2 Capture - No TS&M	$/tonne	56.47	41.56

*Converted to the same basis

- Capture de-rate for BiCAP: 43% < Case 12 (MEA)
- Capture cost for BiCAP: is 26% < Case 12
- TEA to be updated and compared with DOE 2019 baseline (Case 12B, Cansolv)

TEA data above based on BiCAP1 (BiS4) solvent;
BiCAP2 (BiS6) solvent showed better energy performance in experiments

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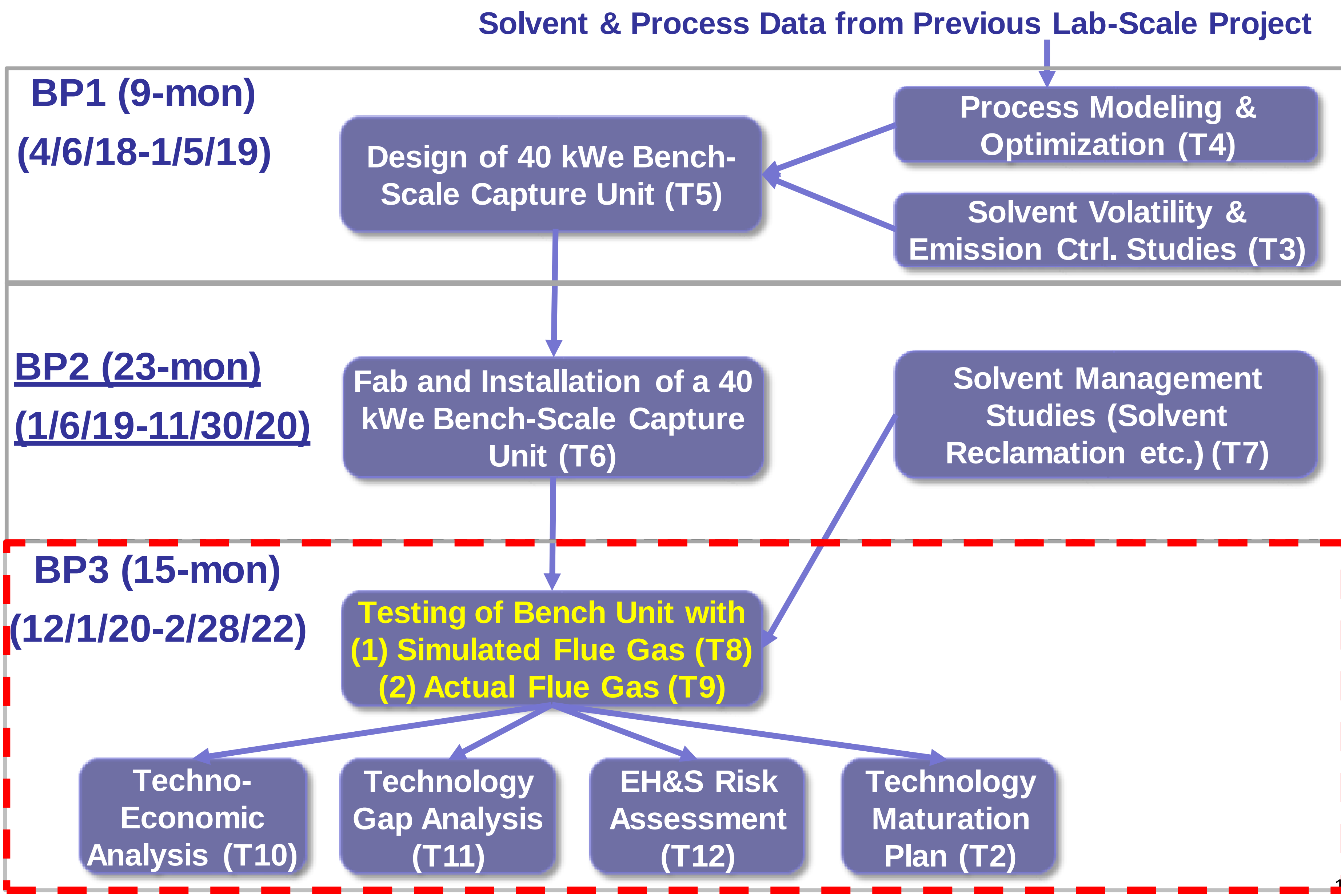
Scope of Work



Main Milestones and Success Criteria

	Basis for Decision/Success Criteria
BP1 (4/6/18-1/5/19)	✓ Solvent vapor and aerosol emissions and mitigation assessed
	✓ Power plant Host Site Agreement issued
	✓ Completion of 40 kWe bench unit design (Design heat duty ≤ ~2,100 GJ/tonne of CO_2 and stripping P ≥ ~4 bar)
BP2 (1/6/19-11/30/20)	✓ Identify suitable options for reclamation of biphasic solvents
	✓ Fabrication and installation of 40 kWe bench-scale unit
BP3 (12/1/20-2/28/22)	✓ Bench unit troubleshooting, commissioning, & testing including parametric testing with synthetic flue gas and 2-week continuous testing with a slipstream of power plant flue gas (Demonstrate continuous operation & total energy use of ≤0.22 kWh//kg)

Install of the bench-scale unit extended and completed in Nov 2020; Testing of the unit in progress (planned to complete by late Dec 2021 / early Jan 2022)

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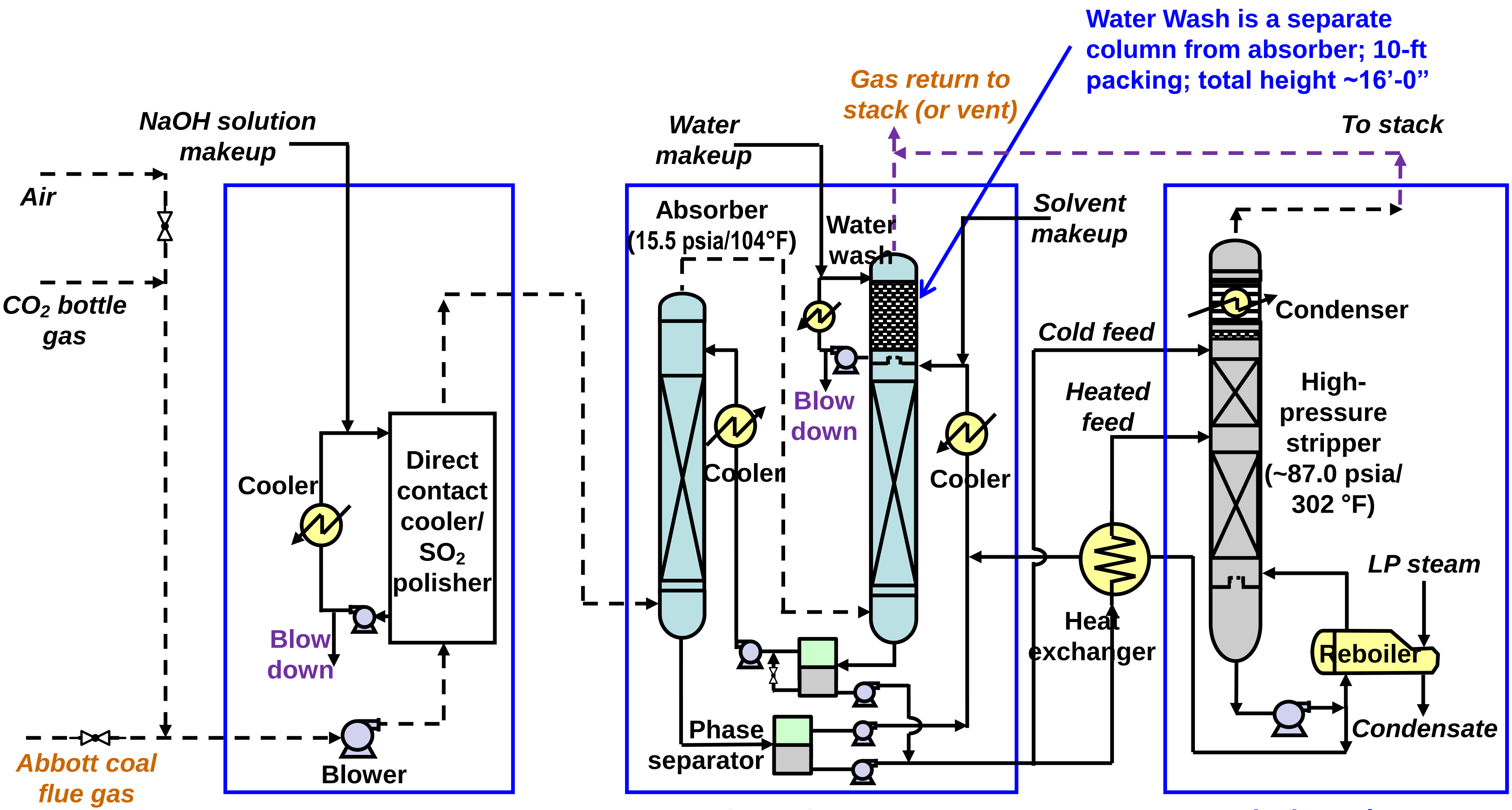
(1) Fabrication and Installation of a 40 kWe Bench-Scale BiCAP Unit at Abbot Power Plant



Flue gas cooling/ polishing treatment

2 absorption columns: Each with 8-in ID × 15-ft packing and a total height ~22'-2"

1 stripping column: 4-in ID × 15-ft packing and a total height ~26'-6"

Schematic of 40 kWe Bench-Scale Capture Unit

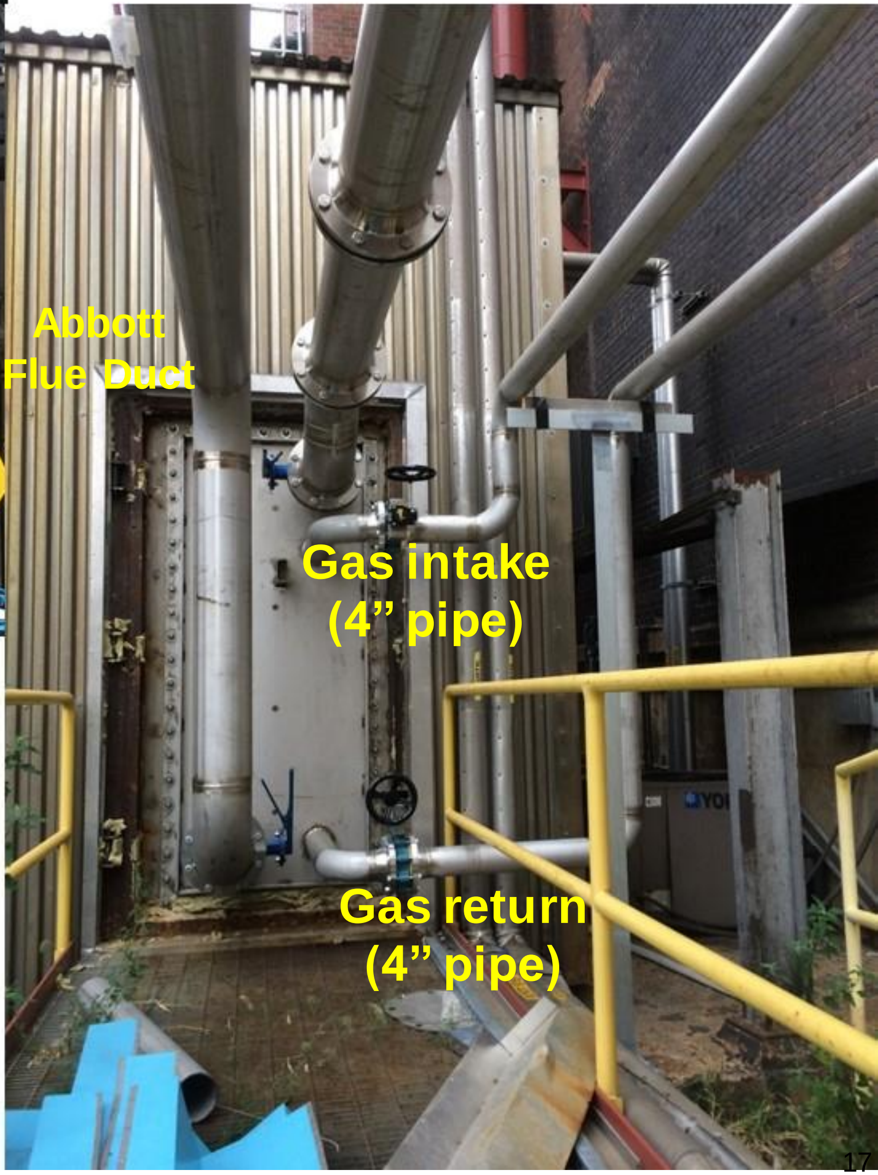
Abbott Power Plant at UIUC

- CHP plant for providing heat & electricity to the campus
- 3 coal-fired boilers, 3 NG-fired boilers, and 2 NGCC units with a total generation capacity of 84 MWe (different flue ducts)
- 3 coal-fired boilers (chain-grate stoker design) burning high-sulfur coal with a combined capacity of 35 MWe
- ESPs and a wet Chiyoda FGD scrubber in place for coal flue gas

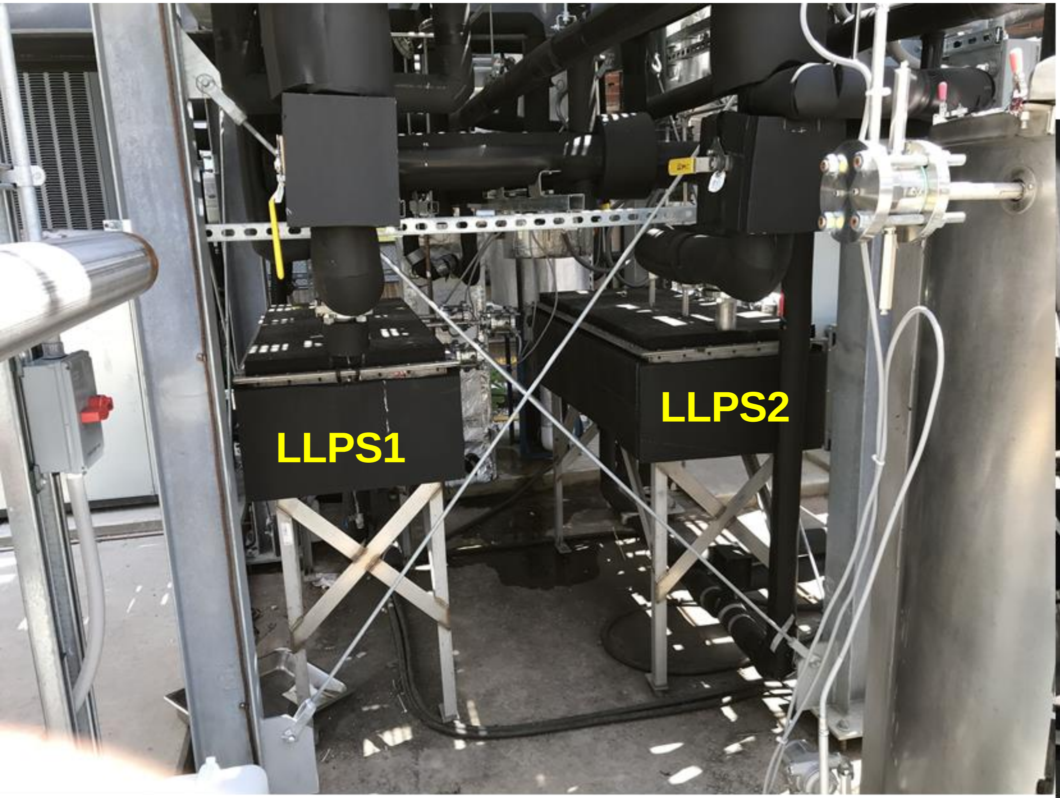
Coal combustion flue gas at Abbott

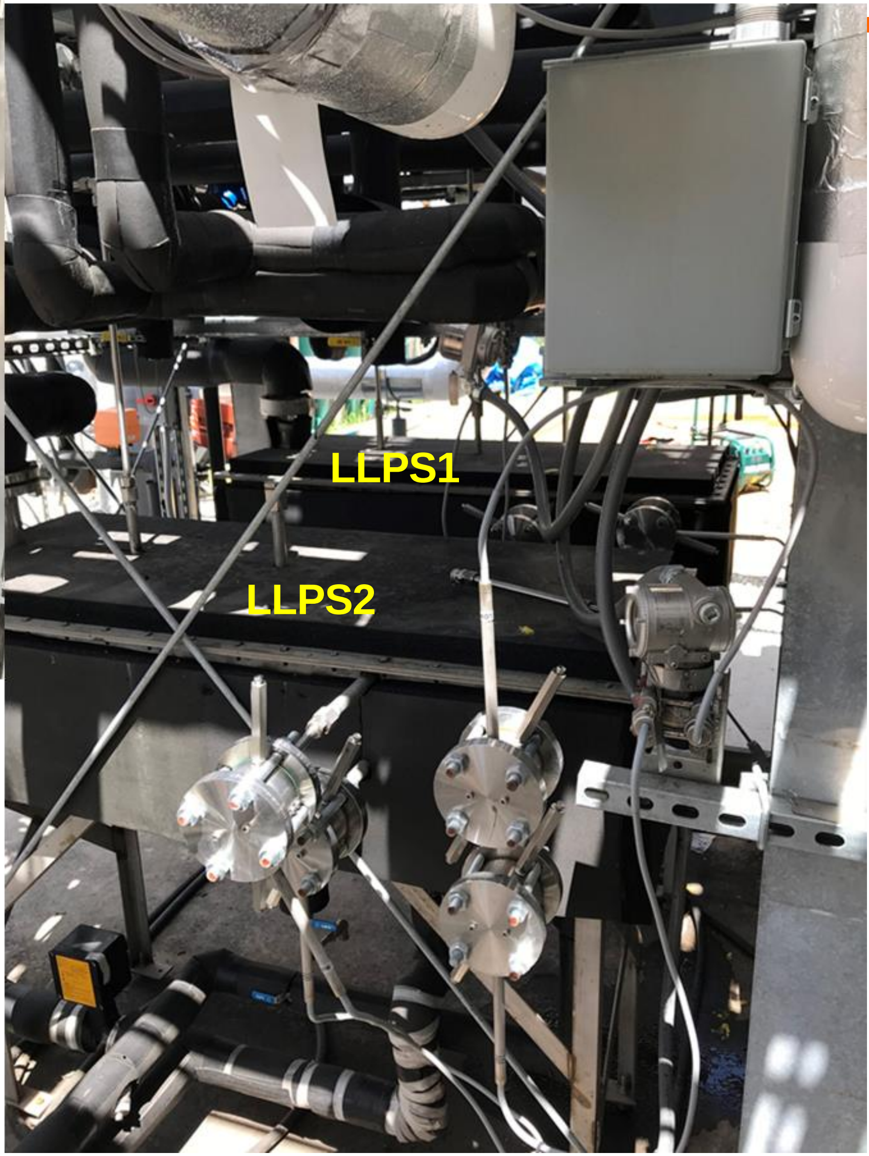
Component	Unit	
CO_2	vol%	5.7
O_2	vol%	10.3
N_2	vol%	69.6
H_2O	vol%	14.4
SO_2	ppmv	68
SO_3	ppmv	15
NOx	ppmv	211
HCl	ppmv	0.73
PM	grains/dscf	0.00223
Temperature	°F	~200

Biphasic Skid at Abbott Power Plant
Abbott Stack
Vent
Water Wash
Stripper
Absorbers
Analytical Trailer
DCC
PLC/ MCC
Blower
Surge Tank



Flue Gas Tie-Ins





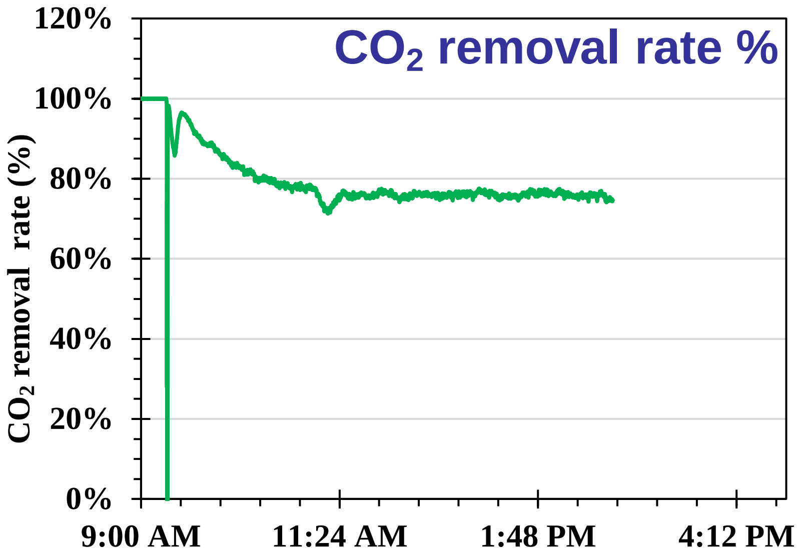
Static Settling Liquid-Liquid Phase Separators (LLPS)

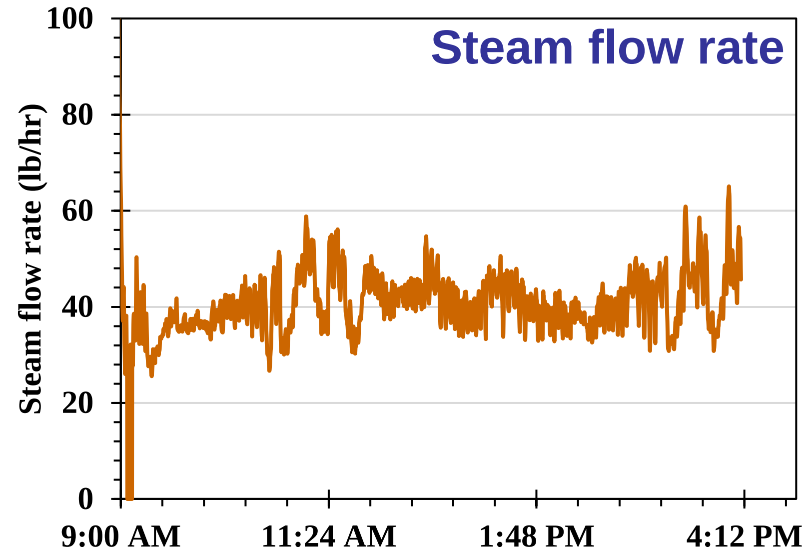
Dedicated gas analyzers (O_2, CO_2, HC, NO_x, SO_2) and FRIT

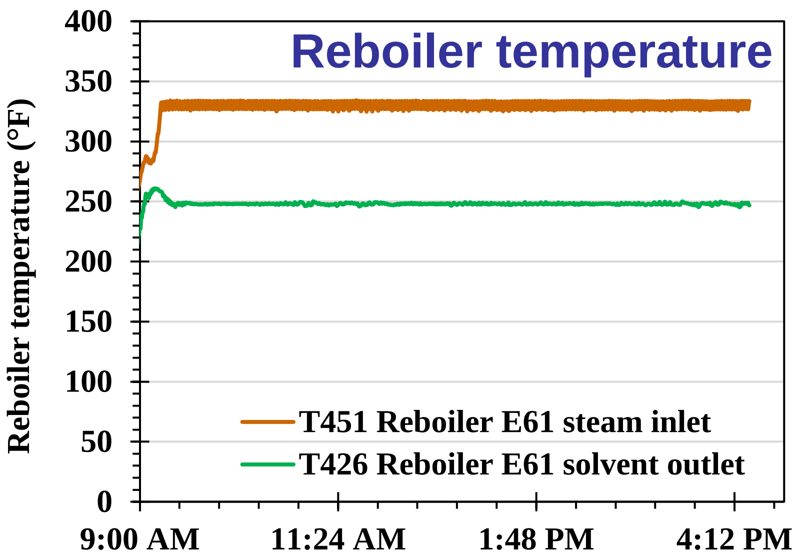
PLC Interface and Gas analysis Inside Analytical Trailer

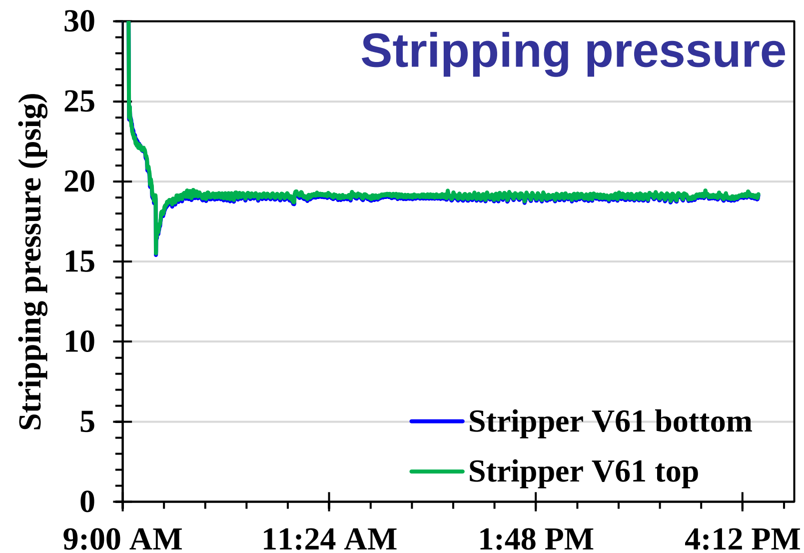
(2) Reference Testing with ~30 wt.% MEA Solvent Using Synthetic Flue Gas (10-12 vol.% CO_2 in Air)

Exemplary test data to illustrate stable operation of the skid:









Results of Parametric Testing for Reference MEA

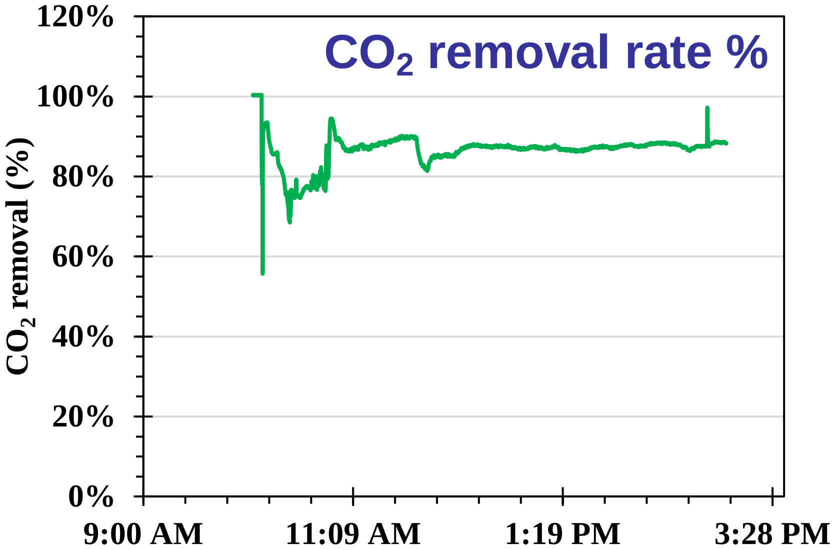
Absorption		
Synthetic flue gas flow rate	SCFM	15-40
CO_2 concentration in flue gas	vol.%	10.4-12.1
MEA concentration	wt.%	24-30
CO_2 rich loading	mol/mol of MEA	0.35-0.44
Temperature in absorbers	°F	76-110
CO_2 removal rate	%	60-98
Desorption		
Steam flow rate	LB/hr	40-115
Stripper reboiler temperature	°F	230-248
Stripping pressure	psig	8-19
CO_2 lean loading in MEA	mol/mol of MEA	0.17-0.38
Heat duty*	kJ/kg of CO_2 captured	4,000 -12,750

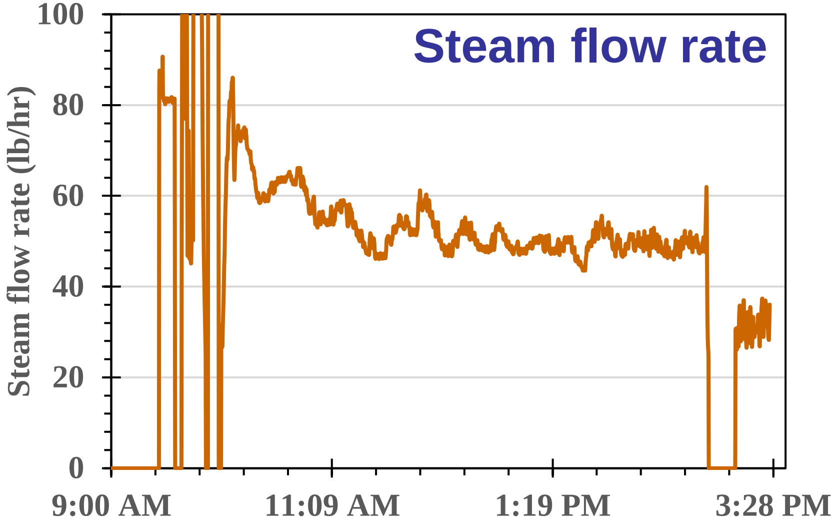
*With the sensible heat use normalized to $\Delta T = 9$ °F

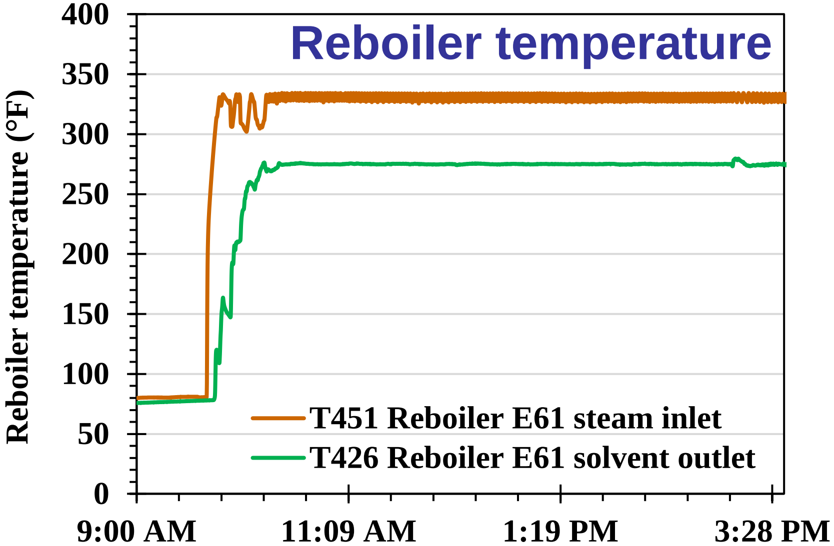
- MEA heat duty: 4,000-4,500 kJ/kg under optimal operating conditions for the skid
- MEA gas treatment capacity: ~1/2 of design capacity for BiCAP solvent because of flooding risk in stripper, indicating larger equipment footprint for MEA than BiCAP

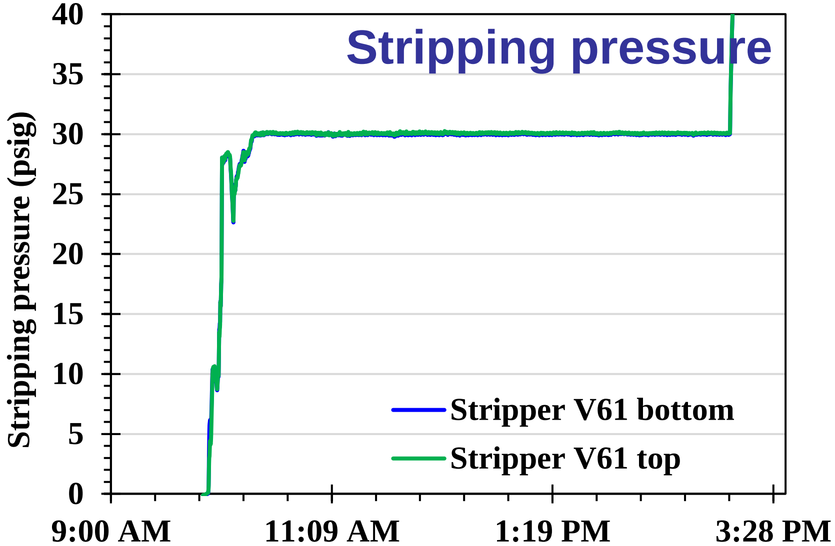
(3) Ongoing Parametric Testing with BiCAP1 Solvent Using Synthetic Flue Gas (10-12 vol.% CO_2 in Air)

Exemplary test data for BiCAP1 solvent:



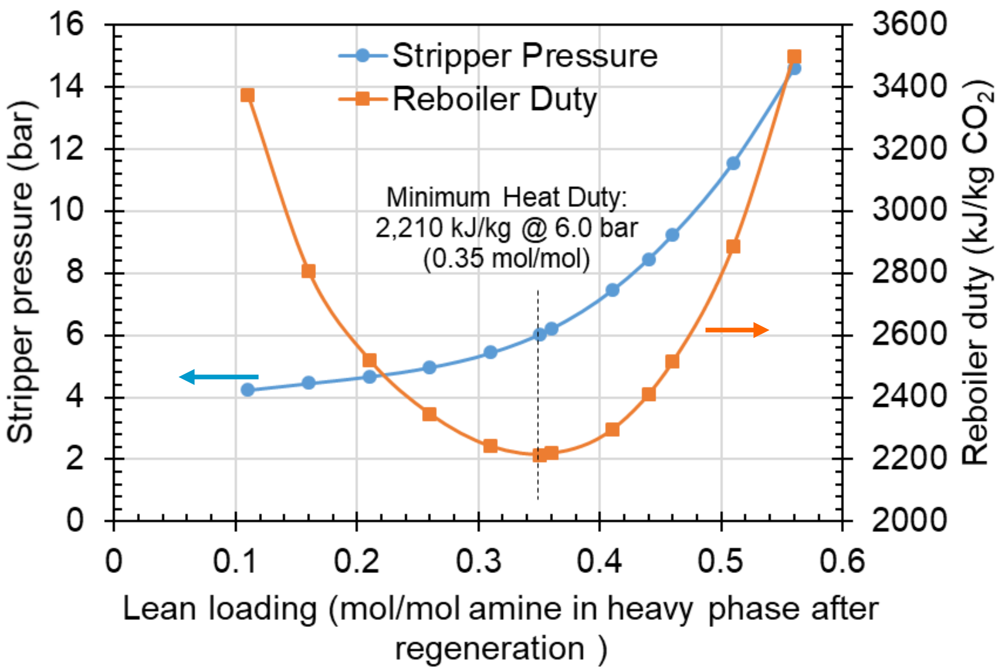






Initial Results of Parametric Testing for BiCAP1 Solvent

- Initial tests showed +90% CO_2 removal achievable and heat duty of 2,220 to 2,750 kJ/kg CO_2 captured
- Initial results consistent with the trend from Aspen Plus modeling

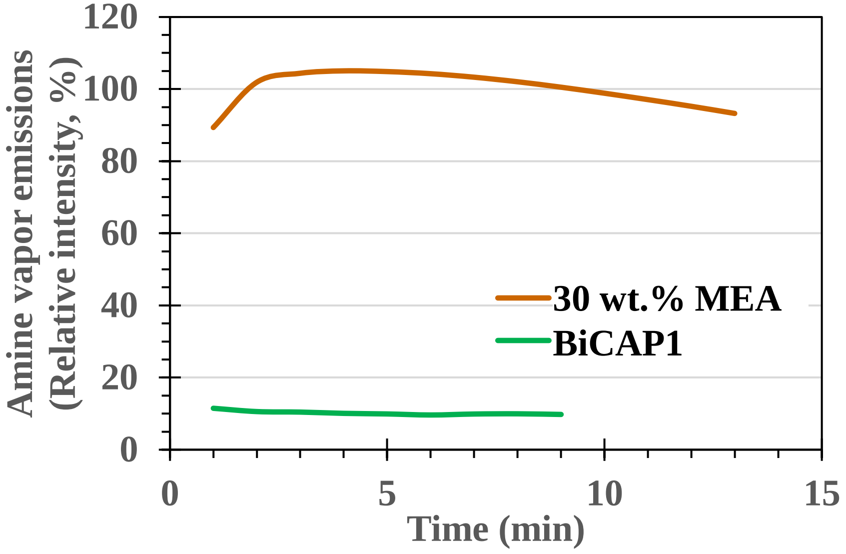


BiCAP1 solvent regeneration in stripper (4" ID x 15' H of Mellapak 250Y packing) at fixed rich loading of 0.73 mol/mol amines in heavy phase and 302°F reboiling temperature

Heat duty of BiCAP2 solvent estimated to be ~10% < BiCAP1

Amine Emissions in Exhaust Gas from Bench-Scale Skid

- Amines/NH_3 vapor emissions from BiCAP1 solvent was 10-15% of that from MEA
- Aerosol emissions during either BiCAP1 or MEA tests with synthetic flue gas (air+CO_2) were insignificant (thousands #/cm^3)
- Comparisons consistent with previous laboratory measurements



Amine vapor emissions in the exhaust flue gas after the water wash column measured by FTIR

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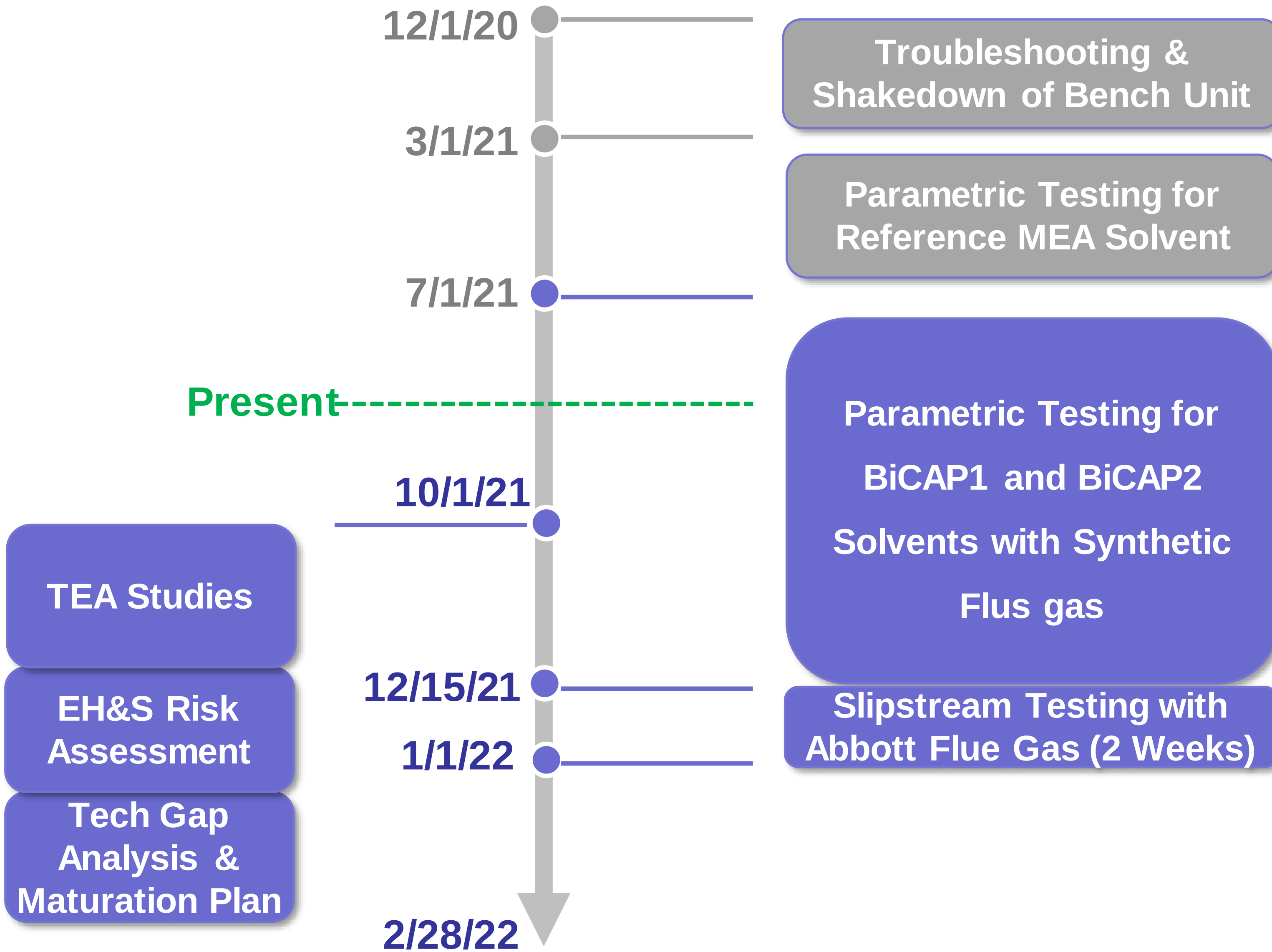
Plans for Remaining Work in the Current Project

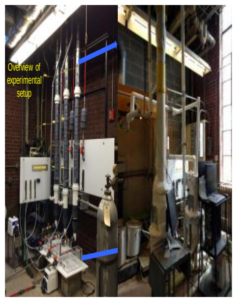


Plans for BiCAP Technology Development and Scale-Up

Current Project

Solvent study, Laboratory

Proof-of-Concept
Funding: *UI (Part of Dissertation Research, 2013-2015)*



10 kWe Testing, Laboratory

Separate Absorber / Stripper
Funding: *DOE / UI (2015-2018)*

40 kWe Testing, Power Plant Slipstream

Bench Scale Close-Loop Unit
Funding: *DOE / UI (2018-2022)*

0.5-1 MWe, Power Plant /Test Center

Small Pilot
Funding: *DOE / UI / Corporate Partners/ State*

10 MWe, Power Plant

Large Pilot
Funding: *DOE / Corporate Partners /State / UI*

Summary

- A 40 kWe bench-scale unit fabricated and installed at Abbott power plant
- Tests with either MEA or biphasic solvent showed stable operation of the bench-scale unit
- Lower gas treatment capacity with MEA than BiCAP solvent for the same unit
- Amine vapor emissions from BiCAP1 solvent was < that from MEA, consistent with previous laboratory measurements
- Initial tests for BiCAP1 revealed heat duty of ~2,200-2,800 kJ/kg of CO_2 captured vs. optimal 4,000-4,500 kJ/kg for MEA solvent
- Bench-scale tests are in progress and will verify if BiCAP2 has better performance than BiCAP1 observed in previous lab-scale tests

Acknowledgements

- **DOE/NETL Project Managers**: Katharina Daniels; Andrew Jones

- **Project Team Members**
  - ✓ **UIUC:** Kevin O'Brien; Paul Nielsen; Hong Lu; Hafiz Salih; Justin Mock; Luke Schideman; Qing Ye; Wei Zheng; BK Sharma; Stephanie Brownstein; Sarmila Katuwal; Vinod Patel; Mike Larson; Mike Brewer; Josh Rubin; Mohamed Attalla
  - ✓ **Trimeric Corporation:** Ray McKaskle; Katherine Dombrowski; Kevin Fisher
  - ✓ **ITG-Henneman:** David Kryszczynski; Darren Timlin; Scott Prause

- **Aspen Technology** for providing free license of aspenONE® software

Appendix 1. Organization Chart

University of Illinois
PI: Dr. Yongqi Lu
Co-PI: Dr. Kevin O'Brien

4 Participating Units at University of Illinois

Trimeric Corporation (Sub-recipient)
- ✓ Process design and equipment specs;
- ✓ TEA support

Illinois State Geological Survey
- ✓ Solvent & process development;
- ✓ Equipment procurement & fab;
- ✓ Skid testing

Illinois Sustainable Technology Center
- ✓ Sample analysis;
- ✓ EH&S studies;
- ✓ Tech maturation plan

ITG Henneman Engineering (Vendor)
- ✓ Detailed engineering design;
- ✓ Support for unit troubleshooting/ startup

Facilities & Services
- ✓ Site construction & skid installation

Abbott Power Plant
- ✓ Host site for bench-scale testing

Appendix 2. Gantt Chart

ID	Task Name	Start	Finish	Resource Names
1	**Task 1.0 - Project Management and Planning**	**4/1/18**	**2/28/22**	**UIUC**
2	1.1 - Project Monitoring and Control	4/1/18	2/22/22	UIUC
3	1.2 - Briefings and Reports	4/1/18	2/22/22	UIUC
4	a - Updated Project Management and Planning	4/30/18	4/30/18	
5	b - Project kickoff meeting	6/30/18	6/30/18	
6	**Task 2.0 - Developing & Implementing a Technology Maturation Plan**	**4/1/18**	**3/31/21**	**UIUC**
7	c - Technology Maturation Plan prepared	6/30/18	6/30/18	
8	**Task 3.0 - Studies of Solvent Volatility and Losses**	**4/1/18**	**12/31/18**	**UIUC**
9	3.1 - Solvent Volatility Measurement	4/1/18	9/30/18	UIUC
10	3.2 - Testing of Solvent Losses in a Laboratory Absorption Column	7/1/18	12/31/18	UIUC
11	d - Volatility measurement and preliminary results of water wash performance obtained	9/30/18	9/30/18	
12	**Task 4.0 - Modeling & Optimization of Biphasic CO2 Absorption Process**	**4/1/18**	**9/30/18**	**UIUC**
13	4.1 - Process Modeling and Optimization	4/1/18	5/15/18	UIUC
14	4.2 - Bench-Scale Unit Process Simulations	5/16/18	6/30/18	UIUC
15	e - Optimal process configuration identified	9/30/18	9/30/18	
16	**Task 5.0 - Design of Bench-Scale Capture Unit**	**7/1/18**	**12/31/18**	**Trimeric**
17	5.1 - Design of Bench-Scale Capture Unit	7/1/18	11/30/18	Trimeric
18	5.2 - Design Review and Approval	12/1/18	12/31/18	Trimeric
19	f - Bench-scale equipment design completed	12/31/18	12/31/18	
20	g - Host Site Agreement obtained	12/31/18	12/31/18	
21	**Task 6.0 - Fabrication and Installation of Bench-Scale Capture Unit**	**1/1/19**	**11/30/20**	**UIUC**
22	6.1 - Solicitation and Selection of a Manufacturing Vendor	1/1/19	6/30/19	UIUC
23	6.2 - Fabrication and Installation of Bench-Scale Capture Unit	7/1/19	11/30/20	UIUC
24	6.3 - Host Site Air Emission EH&S Modeling Assessment	4/1/19	9/30/19	UIUC
25	h - Air emission modeling assessment completed	9/30/19	9/30/19	
26	i - Bench-scale unit fabricated and installed	11/30/20	11/30/20	
27	**Task 7.0 -Solvent Management Studies**	**1/1/19**	**12/31/19**	**UIUC**
28	7.1 - Solvent Degradation and Reclamation Study	1/1/19	9/30/19	UIUC
29	7.2 - CO2 Loading Correlation and In-Situ Measurement	7/1/19	12/31/19	UIUC
30	j- Solvent reclamation option identified	9/30/19	9/30/19	
31	**Task 8.0 - Parametric Testing of Bench-Scale Unit with a Simulated Flue Gas Stream**	**12/1/20**	**11/30/21**	**UIUC**
32	8.1 - Commissioning	12/1/20	2/28/21	UIUC
33	8.2 - Parametric Testing of the Bench-Scale Unit	3/1/21	11/30/21	UIUC
34	k- Bench-scale unit commissioned	2/28/21	2/28/21	
35	l - Parametric testing of bench-scale unit completed	11/30/21	11/30/21	
36	**Task 9.0 - Testing of Bench-Scale Capture Unit at a Power Plant**	**12/1/21**	**1/15/22**	**UIUC,Trimeric**
37	9.1 - Test Preparation	12/1/21	12/15/21	UIUC,Trimeric
38	9.2 - Bench-Scale Testing with Actual Flue Gas	12/16/21	1/15/22	UIUC
39	m- Field test plan prepared	12/15/21	12/15/21	
40	n- Field testing with a slipstream of coal combustion flue gas completed	1/15/22	1/15/22	
41	**Task 10.0 - Techno-Economic Analysis**	**9/1/21**	**2/28/22**	**Trimeric,UIUC**
42	10.1 - Process Analysis and Updating Mass & Energy Balance Calculations	9/1/21	11/30/21	Trimeric,UIUC
43	10.2 - Techno-Economic Analysis	1/14/22	2/28/22	Trimeric,UIUC
44	o - Techno-Economic Analysis topical report completed	2/28/22	2/28/22	
45	p - State-Point Data Table updated	2/28/22	2/28/22	
46	**Task 11.0 - Technology Gap Analysis**	**12/1/21**	**2/28/22**	**UIUC**
47	q - Technology Gap Analysis topical report completed	2/28/22	2/28/22	
48	**Task 12.0 - Environmental Health and Safety Risk Assessment**	**12/1/21**	**2/28/22**	**UIUC**
49	r - Environmental Health & Safety Risk Assessment topical report completed	2/28/22	2/28/22